Observations with the HEGRA stereoscopic system

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The HEGRA system of imaging air Cherenkov telescopes has successfully pioneered the stereoscopic observation technique of extensive air showers. The observational method is briefly described and important results of recent observations of sources of photons with TeV($= 10^{12}$ eV)-energies are summarized: The first detection of a TeV γ-ray signal from the shell-type supernova remnant Cassiopeia A and preliminary results obtained from the observation of strong variability of the extragalactic source Mkn 421 during observations carried out from February to May 2000.

1 Introduction

The sensitivity for detection of TeV-γ-ray sources by observation of extensive air showers in the atmosphere has been largely improved with respect to previously used methods by introducing the air Cherenkov *imaging* technique [1]. With this technique, it is possible to reduce the number of background events induced by charged cosmic rays by applying cuts on the orientation and shape of images in the focal plane of imaging air Cherenkov telescopes (IACTs). By observing air showers simultaneously with more than one telescope the shower geometry can be reconstructed with an accuracy that is unmatched in the field of air shower detectors. The HEGRA collaboration has pioneered successfully the stereoscopic technique with the system of five IACTs operational since 1997 [2] on the Canary island La Palma (2200 m asl, 17.89° W, 27.9°N).

2 Stereoscopic observation method

2.1 Detector setup and data taking

The HEGRA IACTs are placed on the corners of a square with a side length of roughly 100 m with one IACT in the center. The IACTs each have a tessellated mirror with a collection area of 8.5 m^2 and a focal length of 5 m. In the prime focus a matrix of 271 photomultiplier tubes is installed, detecting the faint flashes of air Cherenkov light produced by charged particles of extensive air showers. The telescopes observe co-aligned a patch in the sky with a diameter of $4.3°$ with an absolute pointing accuracy of $\approx 0.007°$.

The data are taken in moonless clear nights with a mean event rate of 15-18 Hertz for observations carried out close to the zenith. The peak detection rate for a photon

source in the zenith with an energy spectrum similar to the one from the Galactic standard candle (Crab Nebula) is at an energy of 500 GeV. Images of all telescopes are read out after two telescopes have been triggered by Cherenkov light from an air shower within a time window of 70 ns [3].

2.2 Reconstruction of shower geometry

The images from the single cameras are cleaned by a *tailcut*, removing pixel amplitudes that are due to sky noise. Images with an integral amplitude of more than 40 photo electrons are parameterized by the first and second moments of the pixel amplitude distribution. The average of the pairwise intersections of the major axes of the image ellipsoids is calculated to determine the direction of incidence of the air shower. Several schemes have been developed to improve the angular resolution [4]. The different methods achieve accuracies ranging from $\theta_{res} = 0.05°$ to $0.1°$ for photon-induced showers. The intersection point of the shower axis with the plane that is perpendicular to the optical axis of the telescopes (*shower core*) is calculated in a similar way by determining the intersection point of the major axes of the image ellipsoids in a different reference frame. Depending upon the method chosen [4] resolutions of 2-10 m for the position of the shower core are achievable.

2.3 Separation of γ-and hadron-induced air showers

The detection of γ-ray sources with the air shower technique is made difficult by background events induced by charged cosmic rays. Since the charged cosmic rays have an isotropic distribution of arrival directions, the background can be suppressed for a point source by a factor that is roughly proportional to $\theta_{res}^2/\Omega_{fov}$, where θ_{res} is the angular resolution and Ω_{fov} is the solid angle covered by the field of view. The imaging technique allows to suppress the background even further by selecting γ-like events by cutting on the shape of the image. Again, the stereoscopic approach allows for an improvement of the capability to separate γ-induced showers from charged cosmic ray events: The *width* of the image ellipsoids is scaled to the expectation value for the image width derived for photon-induced showers using the apparent image brightness and the core position. The average of the scaled width over all telescopes is then used as a cut parameter. In this way hadron-induced air shower events can be rejected to the relative level of a few per cent while retaining 60 % of the photon-induced showers [5].

3 First detection of a TeV signal from Cassiopeia A

The young shell-type supernova remnant *Cassiopeia A* (Cas A) is an exceptionally bright object in the X-ray and radio wavelength bands. A large fraction of this emission of the nearby remnant (3.3 kpc) is attributed to synchrotron radiation from a population of relativistic electrons [6]. The same electron population, which is presumably accelerated in the vicinity of the shock formed at the boundary between the expanding shell and the surrounding interstellar medium, could produce TeV photons via Comp-

ton scattering processes and Bremsstrahlung in the ambient interstellar medium (leptonic origin). Another production mechanism for TeV photons could be due to accelerated nucleons which would produce neutral pions in interaction processes with the interstellar medium. The neutral pions decay into observable TeV photons (nucleonic origin). If the nucleonic origin is verified, this would identify for the first time an important source of Galactic cosmic rays. Motivated by predictions for TeV photon emission derived from these models the HEGRA telescopes have observed Cas A for 234 hours in the observation periods from 1997 until 1999 under good conditions of weather and detector. A crucial task in the analysis of data that have been gathered over a prolonged period of time is the careful treatment of the variations in detector performance.

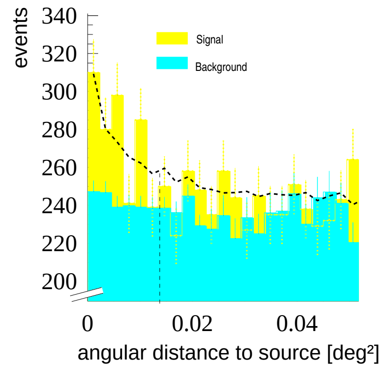

Figure 1: As a function of squared angular distance, the signal from the ON-region is seen above the flat background estimated from the OFF-region. The excess follows the expected shape indicated by the dashed curve.

The result of this exceptionally deep observation and the careful analysis of the data is a signal with a significance of 4.9 σ.[7] Different analysis schemes applied to the same data have confirmed the signal. Systematic checks (source position, energy spectrum of the excess events) have shown that the observed excess is consistent with a signal due to photons (Fig. 1).

The differential energy spectrum derived from the photon signal can be characterized by a power law of the form $dN/dE \propto E^{-\alpha}$ with $\alpha = 2.5 \pm 0.1_{syst} \pm 0.4_{stat}$ between energies of 1 and 10 TeV. The spectral index slightly favors a nucleonic origin of the observed signal but a leptonic origin can not be excluded.

4 Flaring activity of Mkn 421 during Feb-May 2000

The extragalactic sources Markarian 421 (Mkn 421) and Markarian 501 (Mkn 501) have been extensively studied in different energy intervals. These active galactic nuclei (AGN) of the so called *Blazar* type have shown strong variability over all observed energy bands. Simultaneous observations in the X-ray and TeV energy bands reveal a clear correlation of the time dependent fluxes. The observed spectral energy distributions and the correlated variability in X-ray and TeV emission of Blazars can be explained in the framework of a synchrotron-self-Compton model (SSC), where an energetic e^+e^- plasma moving with relativistic bulk speed along the jet axis ($\Gamma = (1-\beta^2)^{-1/2} \approx 10$ to 20) emits synchrotron photons with a peak in the spectral energy

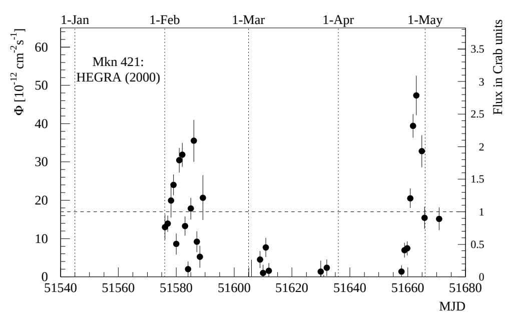

Figure 2: As a function of modified Julian date, the integral flux as measured by the HEGRA system of IACTs is given. The averages are calculated for individual nights.

distribution at energies of 0.1 to 100 keV in the observer's rest frame. By Compton scattering of the energetic electrons off the synchrotron photons TeV photons are produced. As a consequence, the X-ray and TeV fluxes are correlated.

The light curve of measured integral fluxes scaled to the flux measured from the Crab Nebula above 1 TeV [8] ($\Phi_{Crab}(E > 1\,\mathrm{TeV}) = 1.7 \cdot 10^{-11}$ cm^{-2}s^{-1}) is displayed in Fig. 2 for the observational periods from February until May 2000. The remarkable variability in February with strong indication for intra-night variability is complementary to the rather slowly varying TeV flux in the April and May data set. As an example for the intra-night variability, Fig. 3 displays the integral fluxes obtained within 15 minutes time intervals on the 8th of February 2000. The hypothesis of a constant flux has a probability according to a χ^2-test of $3.2 \cdot 10^{-5}$. The TeV energy spectrum of Mkn 421 extends beyond 6 TeV and is well described by a power law. The diurnal energy spectra of April and May show indications for spectral hardening with increasing flux. The energy spectrum derived from the observation of the night with the highest detected flux (April 28$^{\mathrm{th}}$/29$^{\mathrm{th}}$ 2000) can be described by a power law with a photon index of 2.3 ± 0.1. The averaged energy spectrum of the observations in 1997 and 1998 with the HEGRA instruments was softer with a photon index of 3.04 ± 0.07. [9]

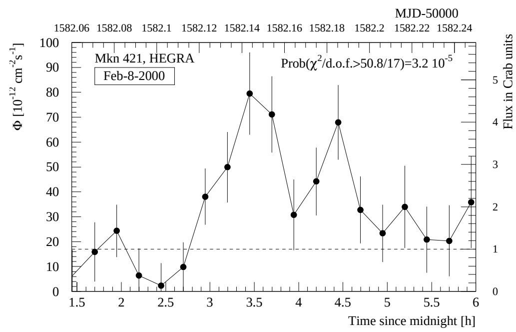

Figure 3: For MJD=51582 (Feb 8,2000), the integral fluxes for intervals of 15 minutes length show a strong increase and a subsequent decrease in flux.

The observations were coordinated with satellite borne experiments like BeppoSAX and RXTE to take data simultaneously in different energy regions. The results of these campaigns will be described in forthcoming publications.

5 Conclusions

The stereoscopic technique has proven to be highly successful in terms of sensitivity and accuracy of shower reconstruction. The unmatched flux sensitivity allowed the detection of Cas A, a weak source of TeV γ-rays after a deep exposure of 234 hours at the level of 3 % of the flux from the Crab Nebula. The light-curve of the extragalactic source Mkn 421 has been measured during two strong flaring periods in February and April/May 2000. The source showed a rapidly changing flux with strong indications for intra-night variations during the February observation period. Within one night (April 28/29, 2000) Mkn 421 showed the largest flux so-far detected by the HEGRA instruments from this source with an exceptionally hard diurnal energy spectrum that can be well described by a power law with a photon index of 2.3 ± 0.1.

1. Weekes, T. C. et al. ApJ, **342**, 379 (1989).
2. A. Daum, G. Hermann, M. Hess et al. Astrop. Ph. **8**,1 (1997).
3. N. Bulian et al., Astrop. Ph. **8**, 223 (1998).
4. W. Hofmann, I. Jung, A. Konopelko et al. Astrop. Ph. **12**, 135 (1999).
5. A. Konopelko et al. Astrop. Ph. **10**, 275 (1999).
6. A.M. Atoyan, F.A. Aharonian, R.J. Tuffs & H.J. Völk A&A **354**, 915, A&A **355**, 211 (2000), and H.J. Völk these proceedings.
7. F.A. Aharonian et al., astro-ph/0102391, accepted for publication in A&A.
8. F.A. Aharonian et al., ApJ **539**, 317 (2000).
9. F.A. Aharonian et al., A&A **349**, 11 (1999).